NBS TECHNICAL NOTE 989

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

A Low-Velocity Airflow Calibration and Research Facility

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The National Bureau of Standards was reorganized, effective April 9, 1978.

Erratum: "A Low-Velocity Airflow Calibration and Research Facility," by L. P. Purtell and P. S. Klebanoff, NBS Technical Note 989.

The expression for Δy on page 10 should be written:

$$\Delta y = \frac{4}{\pi} \frac{f_L}{D} \lambda$$

A Low-Velocity Airflow Calibration and Research Facility

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PREFACE

National concern with problems of the environment, occupational health and safety, mine ventilation, etc., and accompanying regulatory standards, have imposed requirements for instrumentation and calibrations that would provide for more accurate airflow measurements at very low velocities. In order to meet this need the National Bureau of Standards undertook to develop an airflow facility that would provide the technical basis for accurate and uniform aerodynamic measurements at very low velocities. Such a facility can also play an important role in providing significant data in a number of technical areas bearing on the nation's technology. It can be used to good advantage, for example, in conducting aerodynamic research on low Reynolds number flows, boundary layers, flow stability, turbulence, fluid mechanical modeling, etc.

The development of the facility described herein was carried out with support from the United States Bureau of Mines under Contract No. H0133024. The contract was initiated under the Coal Mine Health and Safety Program, and administered by the Pittsburgh Mining and Safety Research Center. The support of the USBM and the cooperation of Dr. George Schnakenberg, Jr., Technical Project Officer of PM&SRC, is gratefully acknowledged.

A LOW-VELOCITY AIRFLOW CALIBRATION AND RESEARCH FACILITY

L. P. Purtell and P. S. Klebanoff

A low velocity airflow facility suitable for the calibration of wind speed measuring instruments and research in aerodynamics is described. The flow facility is of the open-return type with a test section 20 feet (6.1 meters) long, and nominally 3 x 3 feet (0.91 x 0.91 m) in cross section. Special attention was given to obtaining an air stream with a high degree of spatial uniformity and low turbulence with excellent speed control over the range from 10 to 3300 feet (3 to 1000 meters) per minute. Laser-optical methods with appropriate signal processing electronics are employed to establish a primary standard for the measurement of very low velocities. A crossed-beam dual-scattering laser-optical system is used that can operate with either forward or backscattering, and in a frequency shifted Bragg cell mode, or in a non-frequency shifted optical beam-splitter block mode. Detailed performance characteristics of the flow facility and the laser velocity standard are presented.

Key Words: Airflow, calibration, facility, laser optics, low velocity, velocity standard.

1. INTRODUCTION

In recent years concern for environmental quality, and occupational safety and health have generated a need for air flow measurements in lower velocity ranges than previously dealt with. Regulations are being established which are setting more and more rigorous standards as to the levels of airflow to be maintained in connection with problems of health and safety in mines; industrial ventilation, indoor circulation, the "clean bench" problem, etc. As a result, there has been generated the need for more accurate measurements of airflow in a range of velocities which hitherto has not received much attention, i.e., below 152.4 meters (500 feet) per minute with particular emphasis on velocities less than 30.5 meters per minute.

Inherent to these measurement problems is the need for equipment and procedures to provide accurate calibrations which in turn will provide the basis for accurate and reliable instrumentation required for setting appropriate and unambiguous flow standards. It was to meet this need that the National Bureau of Standards, with support from the U. S. Bureau of Mines, undertook to develop a suitable calibration facility for the measurement of very low velocities. In addition, there is also a need for quality technical data for turbulent flows at low Reynolds numbers. It is thus highly desirable that in the development of a capability for low-velocity measurements, consideration also be given to the dual purpose of providing a capability for low Reynolds numbers research on turbulent flows and associated instrumentation.

There are two essential factors to be considered in the proper development of the forementioned capabilities. One is the quality of the air stream, and the other is the method to be used as the primary standard for the measurement of velocity. A suitable facility must avoid blocking effects, have good speed control, and provide an air stream with spatial uniformity and steadiness of flow. The approach in this regard was to apply existing design practices that have been established for relatively high velocity flows in wind tunnels to the development of an airflow facility with very low velocities.

In general, instruments used to measure air flow velocity use some definite and reproducible effect related to the motion, such as a pressure differential or thrust, convective cooling, sound transmission, transmit time of a tracer particle, and more recently light scattering. The Pitot-static tube which utilizes a difference in pressure produced by the motion of the fluid when constructed according to appropriate dimensions has served as a satisfactory primary standard over a wide range of air speeds, but its usefulness is limited to the higher velocities. The uncertainty in reading small pressure differences increases the uncertainty of speed measurements with decreasing speeds, and the Pitot-static tube cannot meet the desired accuracy requirements at the very low

velocities. It was felt that of the various forementioned possibilities, the light-scattering method was the most promising for achieving a velocity standard of sufficient accuracy for a calibration capability at low velocities. The advent of the continuous wave laser provided the coherence, monochromaticity, and intensity of radiation to make this method feasible. It is a method which provides certain advantages in that it is nonintrusive, has a linear response with velocity which can be derived from first principles, and has good spatial resolution. The laser velocimeter is a complex light-scattering system dependent on appropriately processing the light scattered from particles moving with the fluid. However, the programmatic content and associated instrumentation envisaged for the facility made it desirable that it be made to operate without artificial seeding, and that it respond with sufficient sensitivity to ambient scatterers.

With both of the foregoing aspects, i.e., the quality of the air stream, and laser-optics as the primary velocity standard, incorporated as design concepts, the objective was to develop a calibration and research facility over the velocity range of 3-1000 meters per minute. The progress made toward the development of such a facility is summarized herein, and a detailed description and performance evaluation of the airflow facility and laser velocimeter are presented.

2. FLOW FACILITY

2.1 General Description

A special purpose duct, capable of accommodating the more common types of wind-speed measuring instruments without blocking effects, is shown schematically in figure 1. It is an open-circuit duct with room return which pulls air through the duct and exhausts it into the room. It was designed for low velocity flow, i.e., in the velocity range of 3 meters per minute to 1000 meters per minute, and to be able to accommodate laser anemometry. The upper end of the velocity range was selected so as to overlap an existing capability for the calibration of anemometers and Pitot-static tubes. Particular emphasis was given to obtaining a low free-stream turbulence level, and a uniform mean velocity within the test region. The flow facility may be considered to consist of three sections: 1) an upstream or flow conditioning section, 2) a test section, and 3) a downstream or fan-diffuser section. Each section requires special attention in its design in order to achieve the desired performance.

2.2 Flow Conditioning Section

This section is the most important from the design point of view in achieving the desired flow characteristic of low turbulence

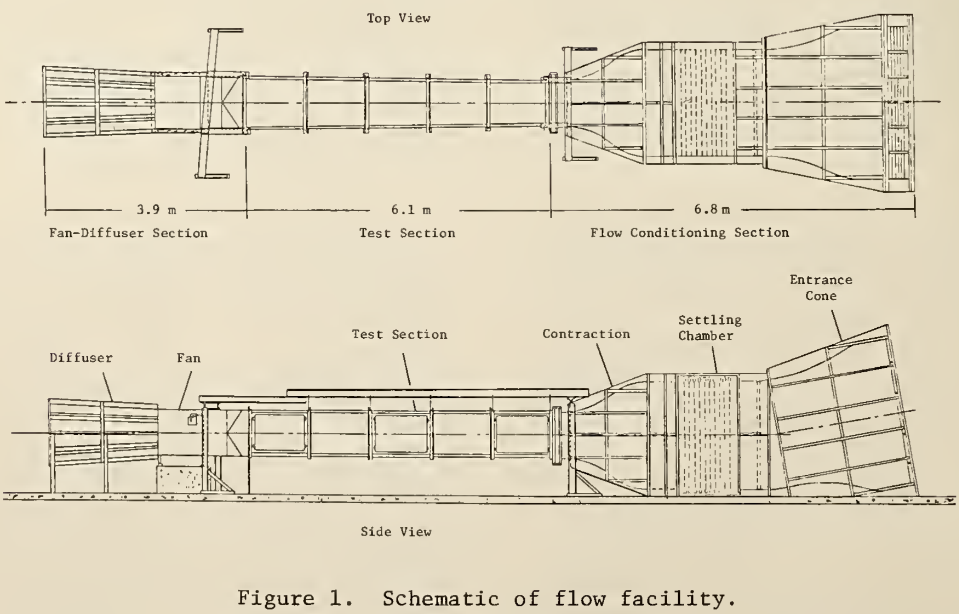

Figure 1. Schematic of flow facility.

level and uniform mean flow (references 1,2). It consists of three subsections: 1) an entrance cone, 2) a settling chamber with honeycomb and damping screens, and 3) a contraction section. All three subsections are made of wood framing with a masonite liner, and are square in cross section.

The design of the facility was constrained to some extent by the available space, and this limitation reflected itself particularly in the unusual design of the entrance cone. There was not sufficient height available to have a conventional entrance cone axisymmetric to the centerline of the facility, and it was tilted up at 12 degrees to the centerline in order to clear the floor. It was felt that this was more desirable than excavating, and relining, and that it could be done without adversely affecting the flow. The entrance cone, however, is axisymmetric to its own centerline, and has an area ratio of 2.14 to 1. The primary function of the entrance cone is to collect the air entering the facility in such a manner as to avoid parasitic vortices, and as shown in section 4, this condition is satisfied and the change in centerline had no noticeable effect on the flow. In order to minimize the stream contamination that may result with an open room-return facility, furnace filters, nominally 20 x 20 x 1 inch (51 x 51 x 2.54 cm), were installed in a lattice-like frame at the front of the entrance cone. Although the laser velocimeter depends on ambient scatterers for its operation, the filters have the desirable features of providing particles that are smaller and more uniform in size than would otherwise have been present, and except for reducing the particle count, the performance of the laser velocimeter is not adversely affected.

The use of a honeycomb and screens as flow-conditioning devices is well-established and adequately documented in the forementioned references. The honeycomb is used to reduce swirl and lateral mean velocity variations. It is made of glass fabric with reinforced plastic with 3/8-inch hexagonal cells, 3 inches long, and is located 21 inches upstream of the first screen. Ten 24-mesh per inch stainless steel damping screens with 0.0075-inch diameter wire were used to reduce the turbulence level. The open-area ratio of 0.672 is more than adequate to avoid the small variations in flow direction in the test section that may be introduced by screens having too high a solidity (reference 3). The screens are spaced 4 inches apart, and are mounted in wooden frames that are recessed in order to avoid disturbance to the flow. The screens can be removed for cleaning through an access door in the side of the settling chamber.

The contraction is perhaps the most critical of the various subsections from the design point of view. Since there is a region in a contraction in which an adverse pressure gradient exists a major design problem is to avoid flow separation. This problem is further complicated by secondary flow in the corners. Another problem is to avoid accelerating the flow in such a manner as to produce "ears" of higher velocity in the mean flow near the walls of the test section. Design information for contractions in very low velocity facilities, i.e., a few feet per minute in the settling chamber, is nonexistent, and a procedure of trial and error was anticipated in obtaining a contraction having good flow characteristics. All four walls of the contraction were constructed with radii of 3.33 feet and 5.0 feet at the upstream and downstream curvatures, respectively, and false adjustable walls were superposed which by screw adjustment permitted modifying the contours by trial and error, as discussed in section 4, so as to prevent flow separation at the very low speeds. The contraction ratio was 5.36 to 1, and the initial configuration consisting of two circular arcs and the contours finally arrived at are shown in figures 2a and 2b. Figure 3 shows a view of the contraction and settling chamber looking upstream from the test section.

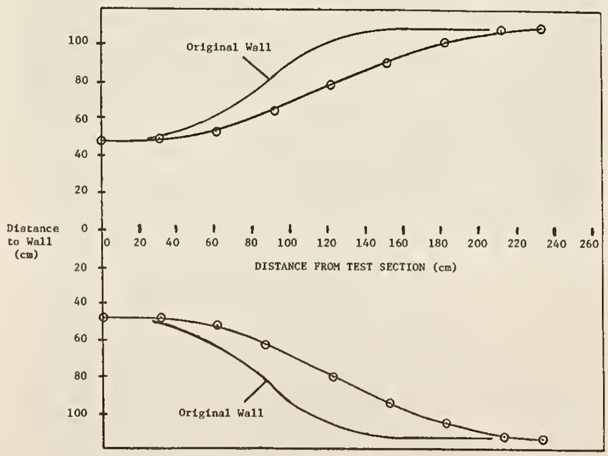

Figure 2a. Contraction contours of sidewalls (top view).

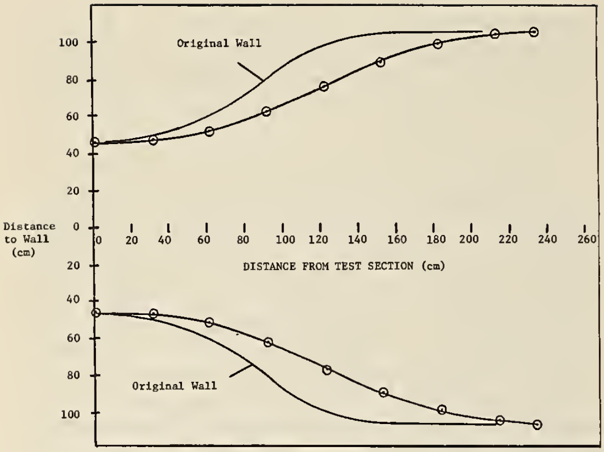

Figure 2b. Contraction contours of upper and lower walls.

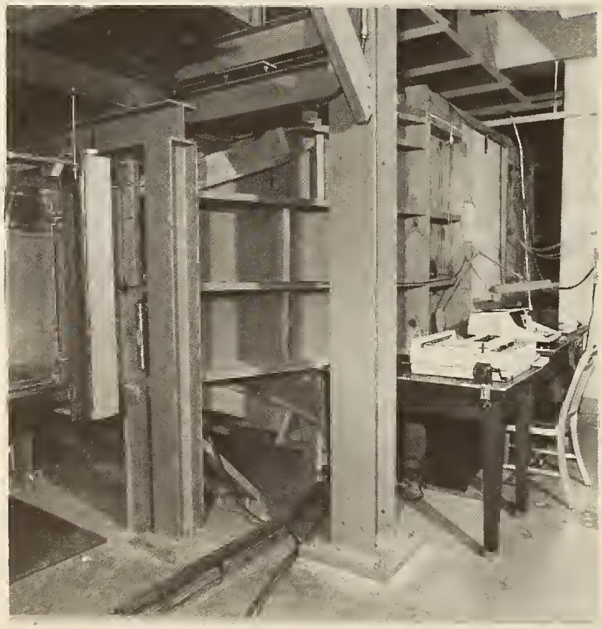

Figure 3. The contraction and settling chamber viewed looking upstream.

Two wall-pressure taps, one located 12 inches downstream from the last screen, and the other located at the entrance to the test section are available to monitor the air speed at the higher velocities, where accurate pressure measurements can be made.

2.3 Test Section

Figure 4 shows a view of the flow facility looking downstream from the beginning of the test section. The test section is nominally 3 feet by 3 feet in cross section, 20 feet long, and is supported from above by two steel trusses, one on each side, extending along its length. This support arrangement allows the traverser for the laser velocimeter, and associated tracks, to be located on the floor. The test section is constructed of plexiglass panels, 3/8-inch thick, mounted in a steel framework. The sidewalls diverge from a separation of 36 inches at the entrance to 39 inches at the exit with the top and bottom walls remaining parallel. Three doors, spaced along its length, on one side, provide access, and at the entrance to the test section access is also provided for the insertion, if desired, of turbulence generating grids.

2.4 Fan and Diffuser

The fan is a 36-inch diameter, variable pitch, twelve-bladed, axial fan directly coupled to a variable speed, 30 HP, DC motor. The DC voltage is supplied by a motor generator set that incorporates a feedback control from a tachometer-generator mounted on the shaft of the fan motor in order to maintain a constant speed. The pitch of the fan and voltage to the motor are remotely controlled, and the resulting arrangement provides excellent control over the range from zero rpm to maximum operating rpm. The fan and motor assembly is mounted on a concrete base and is isolated from the test section by a flexible coupling to minimize vibration. Attached to the exit of the fan is a relatively short diffuser, the length of which was limited by the space available. It has a 5.8 degree included angle and is 6.7 feet long.

3. VELOCITY STANDARD

3.1 General Description

Laser-optic methods, employed in a crossed-beam dual-scattering mode were used to develop a primary standard for the measurement of low velocities. In such a system two coherent beams, of nominally equal intensity intersect to form an interference fringe pattern within a probe volume, and by appropriately processing the scattered light from a particle passing through the volume a measure of the flow velocity is obtained. Involved herein is the assumption that the scattering particle is traveling with the velocity of the fluid. In order to obtain as clean an air stream as possible, compatible with the need for scatterers, no artificial seeding is provided, and ambient

particles are used as scatters. In the dual-scattering mode, if there is sufficient sensitivity, light scattered from the probe volume in any direction may be collected for measuring the velocity of the scatterers. In the present system provision has been made for operating in either forward or back-scattering as required.

The laser and associated optics are mounted on a traverser capable of three-dimensional positioning of the probe volume and signal processing is performed by individual realization, counter-type processors interfaced to a data acquisition system. A photograph illustrating the arrangement of the laser-optic system, associated electronics and traverser is shown in figure 5.

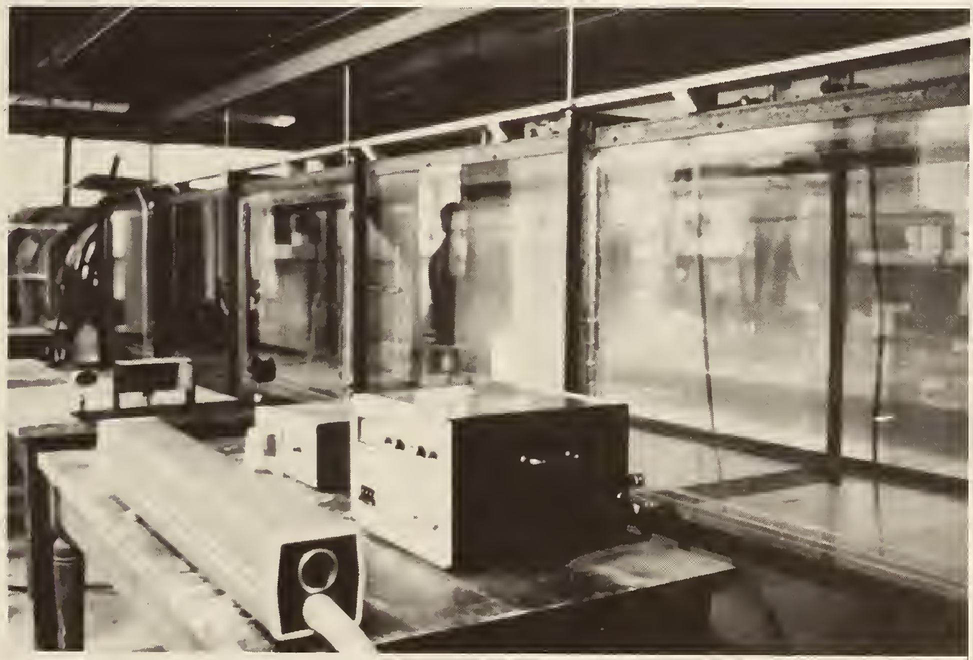

Figure 4. The flow facility viewed looking downstream from the beginning of the test section.

A stationary fringe pattern, however, does not permit resolution of flow direction in certain flow situations, as for example, in the measurement of the velocity component transverse to the mean flow, or where flow reversal may occur, as in separated flows. This directional ambiguity may be resolved by acoustic modulation of the laser beam (reference 4). Acoustic modulation of the laser beam at a known frequency creates a moving fringe pattern with the result that the observed frequency is greater or less than the modulation frequency depending on whether the particle traverses the probe volume in a direction opposite to the moving fringes, or in the same direction. Motion of the fringes also results in an increase in the number of effective fringes that the particle traverses. In order to have this capability the laser-optic system, in addition to employing a beam-splitting optical block that provides a stationary fringe pattern, also incorporates a Bragg cell for acoustic modulation of the laser beam.

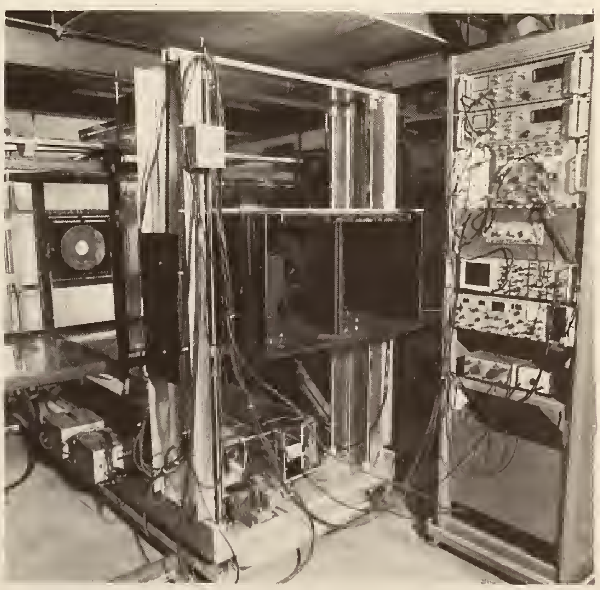

Figure 5. The laser-optic system and signal processing electronics.

3.2 Optics

The optical system for a laser velocimeter capable of being used in a duct large enough for instrument calibration has imposed on it certain requirements beyond those usually encountered in small, laboratory configurations. To position the probe volume virtually anywhere in the duct required a focal length of the projecting and receiving optics of about 3.3 feet. This in turn required large diameter projecting and receiving optics to allow a sufficiently large beam intersection angle and to collect sufficient scattered light for a good signal to noise ratio. In addition, space restrictions required that, in the forward-scattering mode, the scattered light be returned by a spherical mirror to the projecting side of the tunnel in order to focus it on the photomultiplier tube. This arrangement, however, did provide the advantage of having all the optical adjustments on one side of the facility.

The optical configuration in the forward and back-scatter modes is shown schematically in figures 6(a) and 6(b), respectively.

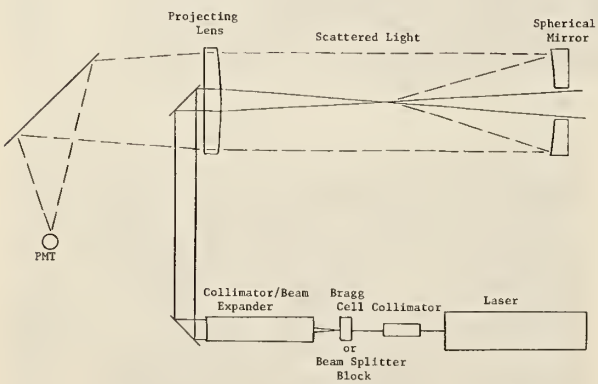

Figure 6a. Optics - forward scatter.

The projecting lens and spherical mirror are 12 inches in diameter with the latter having a 4-inch diameter central opening to avoid having the scattered light interfere with the projected beams. The configuration has been designed to facilitate the change from one mode of operation to the other. To change the system from forward scatter to backscatter requires only the insertion of a second 12-inch diameter lens, as indicated in the figure, and covering the spherical mirror. To change from acoustic modulation, and a moving fringe pattern, to a stationary fringe pattern requires that the beam-splitter optical block replace the Bragg cell in the optical path. It should be noted, however, that adjustment of the various optical components is usually required when changing the mode of operation.

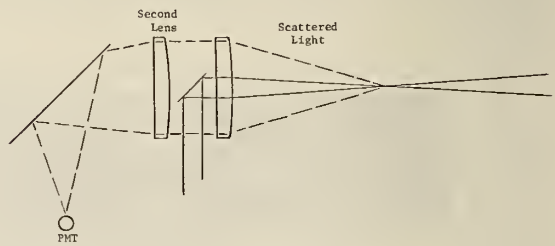

Figure 6b. Optics - backscatter.

The system in the Bragg cell mode of operation is a two-component system, i.e., a two-dimensional Bragg cell, Spectron Development Laboratory, Incorporated, Model 1522*, is used which splits the laser beam in such a manner as to permit the establishment of two sets of moving interference fringes, orthogonal to one another, for measuring the longitudinal and transverse components of velocity. In order to be able to separate the two components in the processing of the resulting signal the modulation frequencies for the two sets of fringes are different, being 25 MHz and 15 MHz for the longitudinal and transverse components, respectively. Although operation with the beam-splitter optical block can in principle be designed for multi-component measurement, at the present time it provides parallel beams for only one set of fringes, permitting only the longitudinal component of velocity to be measured.

A Spectra-Physics, Model 164, 2-watt Argon ion laser is used to provide a laser beam with a wave length of 514.5 nm. The power is varied only as necessary for a particular mode of operation, and in general has ranged from 100 mw to 200 mw. The primary function of the initial collimator is to adjust the location of the beam waist with respect to the intersection of the beams within the probe volume. The ideal condition would be for the waist and intersection point to coincide. The main function of the collimator/beam expander is to produce

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* Brand names of equipment are used solely to provide a reference for performance characteristics and do not represent an endorsement.

enlarged parallel beams sufficiently separated to be focused at an appropriate angle by the projecting lens. However, since the beams entering the collimator/beam expander may be either parallel from the beam-splitter optical block or diverging from the Bragg cell, the input lens must be selected accordingly.

An important parameter in the optical arrangement is the focusing angle, i.e., the angle between the intersecting beams. This angle was determined by scanning the projected beams at two locations along their path, with a photodetector behind a 25 micron precision pinhole for resolution. A typical scan of the distributions of beam intensity at one location for a measured separation of the intersecting beams, is shown in figure 7 for the beam-splitter optical block mode of operation.

change in acoustic velocity of water is approximately 0.16 percent per degree Celcius, and the resulting percent change in angle is equal to the percent change in acoustic velocity. Thus, it is important that Bragg cell transducers be efficient to prevent unnecessary heating of the fluid.

The final step in the optical processing is to have the scattered light focused on a EMI 9781 photomultiplier tube through an adjustable aperture mounted on a three-dimensional positioner.

3.3 Signal Processing

The signal from the photomultiplier tube may be shifted in frequency from the unshifted Doppler frequency by the modulation frequencies of the Bragg cell, or it may be the unshifted Doppler frequency when the beam-splitter optical block is used.

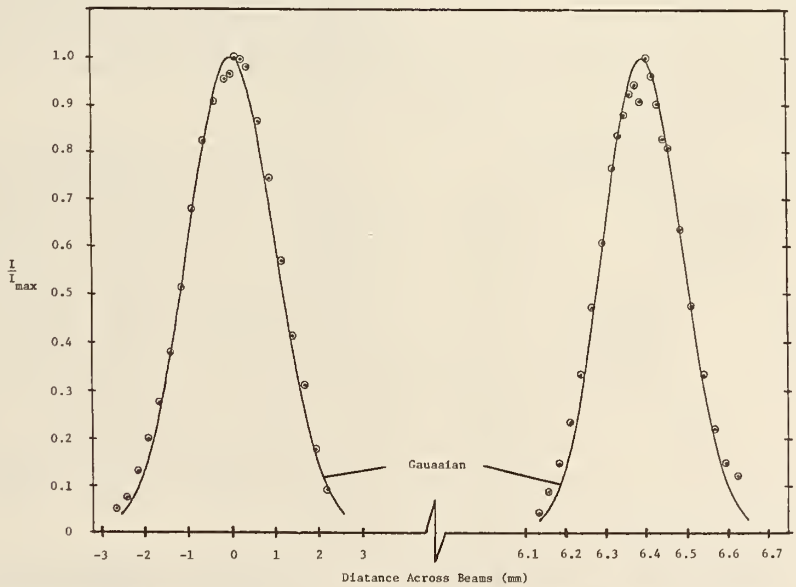

Figure 7. Comparison of intensity profiles of laser beams with Gaussian distribution.

It is seen that the measurements of the light intensity within the beam by this method agree fairly well with the expected Gaussian distribution. The angles for the beam-splitter optical block and Bragg cell modes of operation were 3.85 degrees ± 0.5 percent, and 1.3 degrees ± 1.0 percent, respectively. The larger uncertainty in the angle for the latter can result from imperfections in the optics and beam motion associated with the Bragg cell. Beam wander, for example, may be caused by density variations in the fluid of the Bragg cell. At 22°C the

These two types of signals are quite different and require separate conditioning channels, although the function of each channel is similar. In addition, the signal from the photomultiplier tube also contains a pedestal or amplitude modulating pulse resulting from the Gaussian distribution of light intensity within the laser beam. A block diagram illustrating the signal conditioning electronics is shown in figure 8. In the Bragg cell, two-component mode of operation, two separate processing channels are required. The Bragg cell frequencies of

25 MHz and 15 MHz which have been frequency shifted by the horizontal and vertical components of the Doppler frequency require a wide band, low noise preamplifier for amplification of the signal from the photomultiplier tube, and are sufficiently separated in frequency so as to conveniently permit the isolation of the two components by bandpass filtering. The pedestal frequency is very much lower than the shifted frequencies and is readily removed by this filtering process. In order to obtain adequate system resolution in the Bragg cell mode of operation, particularly at low velocities, as discussed in section 4, it is necessary to have a variable heterodyning capability. This capability is provided by a Tektronix SG-503 variable frequency oscillator and an appropriate mixing circuit. Low-pass filters are used to obtain the difference signals associated with heterodyning, and the resulting signals are appropriately conditioned for data processing.

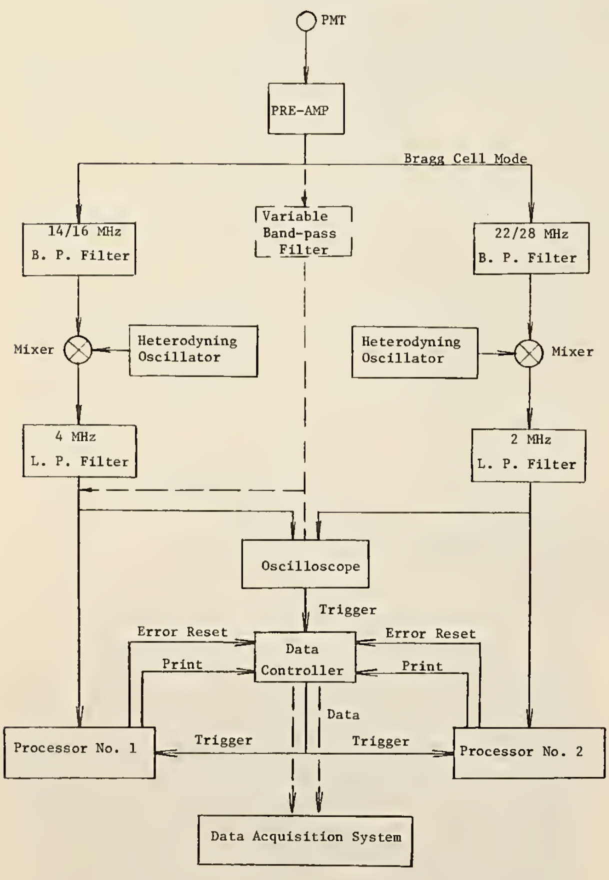

Figure 8. Signal conditioning electronics; Bragg cell mode (solid lines), beam splitter mode (dashed lines).

The procedure for obtaining the signal conditioned for data processing is less involved and more straightforward when the beam-splitter optical block is used. The procedure is further simplified inasmuch as provision has been made for measuring only the longitudinal component of velocity. The signal conditioning channel for this mode of operation consists only of a preamplifier for amplifying the signal from the photomultiplier tube, and a bandpass filter for removing the pedestal frequency. However, since the signal is the Doppler frequency that varies over the velocity range, a variable bandpass filter (Krohn-Hite Model 3103R) is used.

An oscilloscope acts as both a monitor and gating circuit for the conditioned signal. The oscilloscope is adjusted to trigger when sufficiently large signals are present, and routes a gate pulse to the data processors initiating measurement of a "burst" frequency that results from a particle traversing the fringes. The oscilloscope also serves the customary function of system adjustment for maximizing signal quality.

The processors which were constructed for the National Bureau of Standards under contract by the Arnold Research Organization, Incorporated, Arnold Air Force Station, Tennessee, use digital counting and validation circuits to measure an average period between cycles of the "burst." The validation consists of comparing durations of five and eight cycles, respectively, and rejecting any signal for which the comparison is not within a specified limit (reference 5). The signal associated with a "burst" that is accepted appears at the output of the processor in both binary, and binary coded decimal form.

An important aspect of the logistics of data management is that served by the data controller which is an intermediate step between the processor and the data acquisition system. The data controller performs several functions including control of the trigger signal to the processors, control rate of data transfer to the data acquisition system, and determination of simultaneity of processor signals when operating in the simultaneity mode. In the simultaneity mode the data controller will transmit to the data acquisition system only those signals that are processed after one trigger pulse from the oscilloscope. In the event either processor fails to accept a signal, the system resets

automatically to sample again. In the individual mode either or both processors may independently initiate data transfer to the data acquisition system.

Data transmitted to the data acquisition system by the data-controller are received by two interface modules (Wang 705-1A) for translation to a Wang Model 720C programmable calculator. The data are then converted from period to velocity, statistically analyzed, and recorded. Peripherals available to the Wang 720C include plotter, typewriter and card reader.

3.4 Traverser

A three-dimensional traverser which permits positioning the focal volume at any desired location within the test section is shown schematically in figure 9.

rides also by means of ball bushings, thus providing motion in a direction transverse to the test section.

Attached at each end of the upper platform, i.e., on opposite sides of the test section, are vertical assemblies that provide for vertical positioning of the focal volume. These vertical assemblies also consist of a ball bushing and ground rod arrangement on which ride shelves driven by ball screws. On one side the shelf contains the projecting lens, the back-scatter focusing lens, when used, the photomultiplier tube assembly, and various mirrors to appropriately orient the laser beams. On the opposite side of the test section, the shelf contains the spherical mirror mounted on a gimbal mechanism to allow aligning the mirror with the optical axis of the projecting lens.

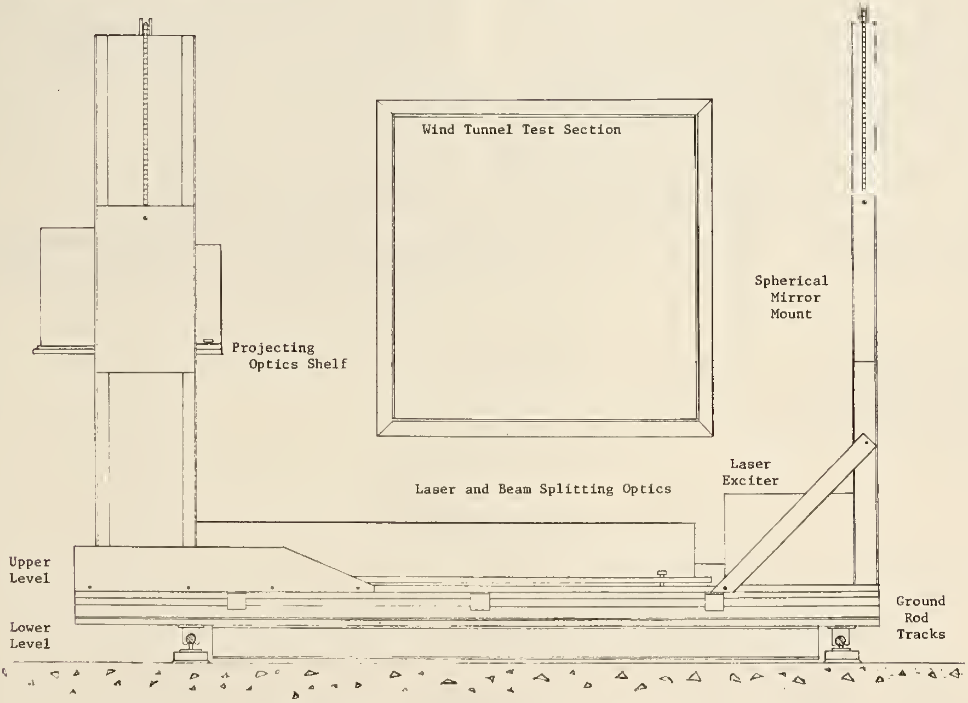

Figure 9. Schematic of traverser for laser-optic system.

Two ground rod tracks mounted on the floor, and running the length of the test section, support and guide a "car" which consists of two platforms that can move relative to one another. The lower platform is attached to ball bushings that ride on the floor rails providing for traversing capability in the longitudinal direction. Mounted to the lower platform are two additional ground rod tracks that run transverse and horizontal to the test section on which the upper platform

The two vertical assemblies are linked by a common drive mechanism so that they move up and down as a unit. Both shelves are partially counter-weighted to provide ease of movement and reduce torsional distortion of the linkage shafts.

4. PERFORMANCE OF LASER-VELOCITY STANDARD

Laser-optic methods have broad capabilities for fluid flow measurement. However,

to fully utilize these capabilities requires attention to numerous details of design and operation, and achieving a proper balance among many parameters. Critical to the resolution and accuracy of the system, and its overall performance, is the focal volume. The dimensions of the focal volume, and the nature of the fringes within, whether stationary or moving, determine the quality of the signal generated by a particle traversing the focal volume. The focal volume is defined by an ellipsoidal surface at which the beam intensity is $1/e^2$ of its maximum value. Implicit in this definition is that the diameter of a Gaussian beam is given by the $1/e^2$ intensity.

The dimensions of the focal volume are a function of the wavelength of the laser light, λ, the focal length of the projecting lens f_L, the diameter of the beams at the projecting lens, d, and the angle of intersection of the beams, θ, (reference 6). The three axes, Δy, Δx, and Δz, where Δy is vertical and transverse to the optical axis, Δx is horizontal and transverse to the optical axis, and Δz is in the direction of the optical axis, are given by

$$\Delta y = \frac{4}{\pi} \frac{f_L}{d}$$

$$\Delta x = \frac{\Delta y}{\cos \theta/2}$$

$$\Delta z = \frac{\Delta y}{\sin \theta/2}$$

The fringe spacing, L, is given by

$$L = \frac{\lambda}{2 \sin \theta/2}$$

and from the above formulations, the number of fringes, N, in the volume is

$$N = \frac{4}{\pi} \frac{D}{d}$$

where D is the beam separation at the projecting lens. The pertinent characteristics of the focal volume in the Bragg cell, and optical beam splitter block modes of operation are given in Tables 1 and 2 below.

Table 1

Characteristics of the Bragg Cell Mode of Operation

Frequency Shifting:	Two-component, waterfilled Bragg Cell (Spectron Development Laboratories), 15 and 25 MHz.
Projecting Lens:	Focal length = 1 m; diameter = 30 cm.
Beam Diameter at Lens:	6.2 mm.
Beam Separation at Lens:	2.27 cm.
Angle of Beam Intersection:	1.3°.
Focal Volume:	Δx = 0.10 mm Δy = 0.10 mm Δz = 9.3 mm
Fringe Spacing	22 μm.

Table 2

Characteristics of the Beam-Splitter Mode of Operation

Projecting Lens:	Focal length = 1 m; diameter = 30 cm.
Beam Diameter at Lens:	4.6 mm.
Beam Separation at Lens:	6.7 cm.
Angle of Beam Intersection, θ:	3.85°.
Focal Volume:	Δx = 0.14 mm Δy = 0.14 mm Δz = 4.2 mm
Fringe Spacing:	7.65 μm.

In the optical beam-splitter block mode of operation, i.e., without frequency shifting, the longitudinal component of velocity, U, is simply

$$U = L/T$$

where T is the average period of a particle crossing the focal volume as measured by the processor. Consequently, the resolution in this mode of operation depends solely on the resolution in determining L and T. The uncertainty in measuring the average burst period, T, depends on the processor setting, and is 0.1 nsec for frequencies above 500 kHz and 0.01 μsec for frequencies below 500 kHz. The maximum uncertainty in the measurement of T is 0.5 percent, which is well within the desired accuracy of ± 1.0 percent for the speed range covered by the flow facility. The major uncertainty over the speed range, therefore, in the stationary fringe mode of operation arises from the uncertainty in the fringe spacing. Several methods were used to determine L. One method consisted of direct measurement of the beam intersection angle as described in section 3.2. A second method involved measuring the velocity associated with a rotating disc. An acrylic disc attached to an electric motor rotating at a measured rate was located such that one of its sides intersected the focal volume at a specified radial location. Imperfections and dust on the surface served as scatterers for the laser-optic system which measured their velocity. By this method the fringe spacing could generally be determined to 0.5 percent. This method, however, holds the promise of being improved by greater precision in determining the rotational speed of the disc and radial location of the focal volume. The third method used to determine the fringe spacing is similar in principle to the second. It consisted of comparing the air velocity of the flow facility by the laser-optic system, U_L, with those obtained by the Pitot-static tube velocity standard, U_P, which has more than adequate resolution at the higher flow velocities. The Pitot-static tube has a 4 to 1 modified ellipsoidal nose (reference 7) with an external body diameter of 0.309 inch, and an impact opening of 0.0625 inch. The results of such a comparison are shown in figure 10. In this connection, it should be noted that the measurement of velocity by the laser-optic system was made with fringe spacing as determined by direct measurement of the focusing angle. The relatively large scatter at the lower velocities, i.e., below 100 m/min is primarily a consequence of the uncertainties associated with Pitot-static measurements alluded to in the Introduction. The square-symbols denote the average values, and the dashed curve indicates the trend of the impact pressure of the Pitot-static tube to increase at low Reynolds numbers due to viscous effects. The Reynolds number based on the internal diameter, a, (i.e., Ua/ν, where ν is the kinematic viscosity) is 104 at U = 61 m/min.

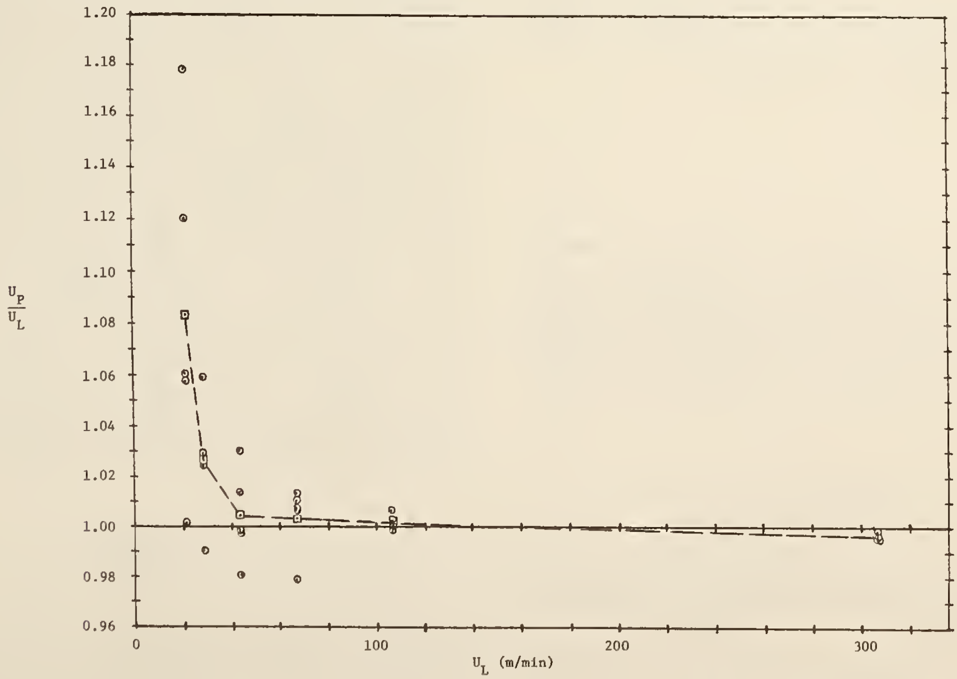

Figure 10. Comparison of laser velocity standard with Pitot-static tube velocity standard.

The data are too limited to draw definitive quantitative conclusions as to the magnitude of the viscous effect at low Reynolds numbers but they do demonstrate the utility of the facility for low Reynolds number investigations. Be that as it may, at the higher velocities, for example, above 100 m/min, the agreement between the laser system and the Pitot-static tube is excellent. Thus, comparison with the Pitot-static tube at higher velocities, affords a convenient method for monitoring and determining the focusing angle within the required accuracy. It is particularly advantageous when operating in the Bragg cell mode in view of the greater uncertainty associated with the direct measurement of a much smaller angle. It is still desirable, however, that future effort be directed toward increasing the focusing angle in the Bragg cell mode of operation. All three methods of determining the fringe spacing gave values that agreed to within 0.5 percent.

Evaluating the resolution and accuracy in the Bragg cell mode of operation is somewhat more complicated than that discussed above in that an additional consideration involving the Bragg cell and heterodyning frequencies is introduced. In the Bragg cell mode of operation the fringes are not stationary and move at a velocity

$$V_f = Lf_c$$

where f_c is the Bragg cell frequency. The average period, T_f, of a particle crossing the focal volume thus becomes

$$\frac{1}{T_f} = \frac{U}{L} \pm f_c$$

depending on whether the fringes are moving in a direction opposite to, or in the same direction as the traversing particle. However, the period of the signal, T_S, measured by the processor has been conditioned by the heterodyning frequency, f_H, with the result that

$$\frac{1}{T_f} = \frac{1}{T_S} + f_H$$

and the longitudinal component of velocity is given by

$$U = L(\frac{1}{T_S} - \Delta f) \qquad (1)$$

where Δf is the difference, $f_c - f_H$, and the fringes are moving in a direction opposite to the traversing particle. The uncertainty in the measurement of velocity in the Bragg cell mode of operation can therefore be expressed as

$$\frac{\partial U}{U} = \frac{[\frac{U}{L} + \Delta f]^2}{\frac{U}{L}} \cdot \partial T_S \qquad (2)$$

in which the fringe spacing or beam angle and the resolution of the processor, ∂T_S, may be regarded as being predetermined for a given arrangement, and the remaining factor requiring evaluation is Δf and its dependence on U. In order to avoid errors associated with the arithmetic difference of two nearly equal large quantities, the difference $f_c - f_H$, in the present arrangement is measured directly. This difference is monitored by a seven digit counter which provides a resolution of ± 0.1 Hz over the required range. Thus, the resolution depends primarily on optimizing Δf to a minimum as a function of velocity such that the resulting signal is within the higher resolution range, i.e., $1/T_S > 500$ kHz, for as much of the velocity range as possible.

Several factors, however, impose constraints on Δf. In measuring time dependent flows, for example, where the velocity may change sign, the frequency shift should not be removed or directional ambiguity may occur. In addition, in time dependent flows, attention should be given to not having the signal too close in frequency to a filter cut-off frequency or information may be lost. The important constraint imposed on Δf in the present arrangement arises from the small focusing angle. As a result there are only five fringes in the focusing volume and this number is not sufficient for operation of the processor. The processor requires for its logic nominally ten cycles of information, and in general it is desirable that more than ten be available to permit triggering at higher level signals thus improving the signal to noise ratio. The number of effective fringes, N_S, with frequency shifting, is given by

$$N_S = N[\frac{L\Delta f}{U} + 1] \qquad (3)$$

and the minimum threshold value of Δf is

$$\Delta f_m = (\frac{N_m}{N} - 1)\frac{U}{L} \tag{4}$$

where N_m is the specified minimum number of fringes that the particle crosses. It is noted from equation (2) that for a given system there will be a value of U above which $(U/L + \Delta f_m)$ is greater than 500 kHz and ∂T_S will be 10^{-4} μs. The threshold value, U_m, above which $\Delta f_1 = \Delta f_m$ is

$$U_m = \frac{5 \times 10^5 LN}{N_m} . \tag{5}$$

In the event $U < U_m$, the uncertainty in T_S will become 10^{-2} μs rather than 10^{-4} μs unless Δf is increased above Δf_m such that $(U/L + \Delta f)$ is greater than 500 kHz. In view of the emphasis placed on low velocities in the present facility it is desirable to resolve the question as to which setting of the processor will produce the least uncertainty, $\partial U/U$.

Since for either value of ∂T_S the minimum value of $\partial U/U$ is obtained by minimizing Δf, the uncertainties, $\partial U/U$, may be compared by setting

$$\Delta f_1 = 5 \times 10^5 - \frac{U}{L} \tag{6}$$

for $\partial T = 10^{-4}$ μs, and

$$\Delta f_2 = \Delta f_m \tag{7}$$

for $\partial T = 10^{-2}$ μs. The ratio, R, of the uncertainties $\partial U/U$, for the conditions expressed in (6) and (7) is

$$R = 10^{-2}(\frac{U_m}{U})^2 \tag{8}$$

It is seen from equation (8), and illustrated in figure 11, that only for a limited range of U, i.e., $0.1\ U_m < U < U_m$ should Δf be greater than Δf_m, and that at values of $U < 0.1\ U_m$ less uncertainty, $\partial U/U$, is obtained with $\partial T_S = 10^{-2}$ μs rather than 10^{-4} μs. The resulting uncertainty in U using an optimum setting for Δf is small, being 0.15 percent. When the uncertainty in U includes the contribution from L, arising from the uncertainty in determining the focusing angle, the contribution from L is dominant. As a result, the uncertainty in U in the Bragg cell mode of operation with Δf and L considered as random variables, is approximately 1.0 percent over the speed range. Similar considerations for the beam-splitter mode of operation give an uncertainty in U that varies from 0.5 to 0.7 percent over the speed range.

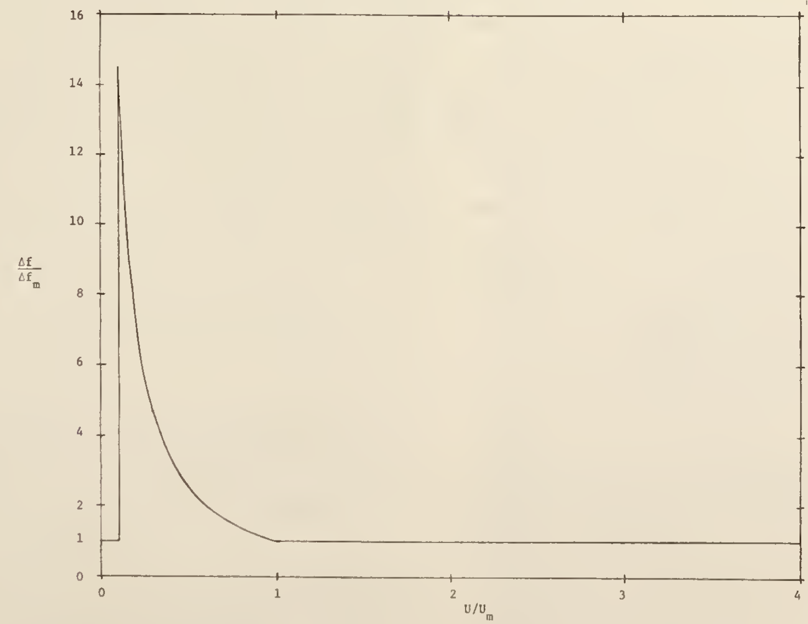

Figure 11. Optimum difference between Bragg cell and heterodyning frequencies.

The foregoing comments as to the effect of Δf and L on an individual realization of velocity are particular to the present arrangement but the approach should be generally applicable. However there are many factors contributing to scatter in velocity measurements by laser-optic methods other than the two discussed above. Some of the more important of these are optical abberations, improper focusing of the laser beam, impurities or density variations in the Bragg cell, particle effects and vibration. Inasmuch as the airflow in the facility, as discussed in section 5 is uniform and has low turbulence level, it provides an excellent medium for assessing the composite effect of the variables affecting the scatter in the velocity data obtained with the laser system.

The magnitude of the random variations in individual realizations of velocity, at a fixed speed, resulting from the above effects, can best be characterized by the standard deviation of the data. Assuming no systematic error, the standard deviation, coupled to the number of realizations and the probability distribution function determine the degree of confidence that can be placed in measuring a limiting mean value. The number density of scattering particles, since seeding is not employed, varies greatly from day to day, and the number of individual realizations per minute, for example, ranges from 30 to 300 at a velocity of one meter per second.

The data are processed by the data acquisition system described in section 3.3 to provide the velocity of individual realizations, their number, the cumulative mean, and the standard deviation. The random variations about the mean have a normal (Gaussian) probability distribution function with standard deviations over the speed range in the beam-splitter and Bragg cell modes of operation of 1 and 5 percent, respectively. As a result, operation in the beam-splitter mode, for example, would require 30 realizations for a 99 percent confidence level that the sample mean velocity be within ± 0.5 percent of the true mean value. In the Bragg cell mode 180 realizations would be required for a 99 percent confidence level that the sample mean be within ± 1.0 percent of the true mean velocity. The mean velocity can therefore be measured to a high order of accuracy, assuming no systematic error, solely by increasing the number of realizations constituting the sample mean. However, measurement of turbulence intensity, i.e., the rms value of fluctuations in velocity relative to the mean velocity is limited by the magnitude of the "noise" or base level standard deviation. The present system, therefore, is limited to the measurement of relatively high turbulence levels, with perhaps a correction for the "noise" level when appropriate. Considerable reduction in the standard deviation would be required to make the system competitive with hot-wire anemometry for the measurement of low turbulence levels. It should be noted, however, that the laser method for measuring turbulence can find application in a variety of flow situations in which hot-wire anemometry cannot be satisfactorily applied.

5. PERFORMANCE OF FLOW FACILITY

The important factors in evaluating the performance of the flow facility, other than assuring that the velocity range meets design requirements, are the uniformity of the flow, the turbulence level, and the degree of unsteadiness of the airstream. The latter is regarded as distinct from the turbulence, and its occurrence is generally associated with fan performance or the presence of large scale, intermittent disturbances in the flow circuit.

The fan drive was monitored with a tachometer and no difficulty was encountered in maintaining a constant rpm over the speed range. However, at a velocity below 0.6 m/s in the test section, and with the contraction in its initial configuration (see section 2.2), severe fluctuations in velocity were observed. These fluctuations were highly intermittent in time and location, and thus were difficult to characterize. Measurements made with a hot-wire anemometer indicated that the fluctuations in velocity were not due to problems with fan pitch or rpm, but that they resulted from an unsteadiness in the flow upstream of the test section. One of the factors that played a role in producing this unsteadiness, and perhaps the most critical, was the upstream concave curvature of the contraction, and the associated intermittent separation of the flow from the walls of the contraction. In regard to this effect, the procedure was to adjust the adjustable panels which were attached to the inside of all four walls of the contraction in such a manner as to decrease the upstream curvature until the speed at which fluctuations in velocity were observed was a minimum. Below this minimum speed, which was about 0.3 m/s, disturbances due to leaks were also observed to occur. The flow facility operates at below atmospheric pressure and it was observed that leaks into the facility around the door leading to the screens in the settling chamber were sufficient to cause fluctuations in velocity in the test section. Sealing these leaks reduced the level of disturbances considerably.

Further hot-wire measurements at these low velocities indicated that intermittent flow disturbances still existed but they were much more infrequent, and at the beginning of the test section they were confined to the region of the wall. These disturbances extended to greater and greater distances laterally in a downstream direction, however, at one meter downstream from the beginning of the test section they did not materially affect the extent of the calibration "window." These latter disturbances were attributed to temperature inhomogeneities, and it was possible to prevent or minimize their occurrence by thoroughly mixing the air before it entered the facility or by operating the facility, for a time, at a moderately high speed.

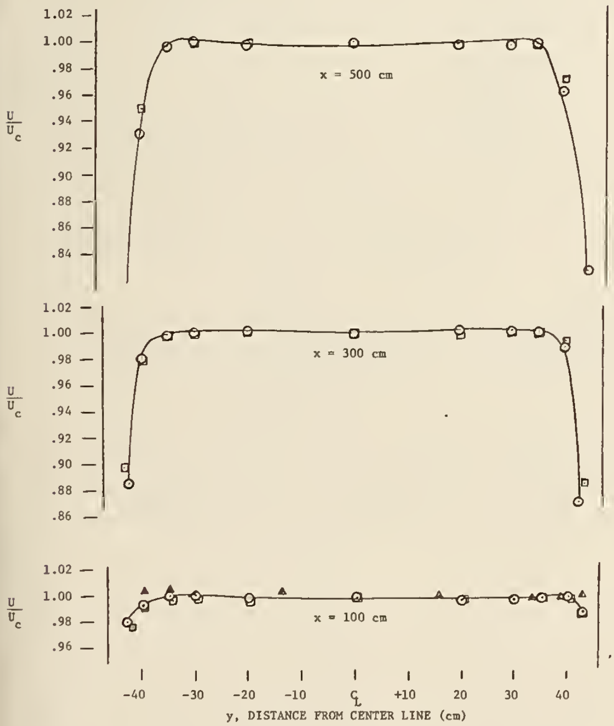

Figure 12. Velocity distributions (horizontal through centerline), ⊙ U_c = 322 m/min, Pitot-static tube, △ U_c = 322 m/min, laser velocity standard, ⊡ U_c = 567 m/min, Pitot-static tube.

Measurements of distributions of mean velocity, U, in the horizontal direction, y, and the vertical direction, z, about the centerline of the duct are shown in figures 12 and 13 , respectively. The distributions shown are for centerline velocities, U_c, of 322 m/min, and 567 m/min, and at different downstream distances, x, from the beginning of the test section of 100 cm, 300 cm, and 500 cm. The decrease in velocity that occurs near the wall reflects the presence of the boundary layer through which the mean velocity decreases to zero at the surface. Measurements with both a Pitot-static tube, and the laser system were made in the process of evaluating the uniformity of the flow.

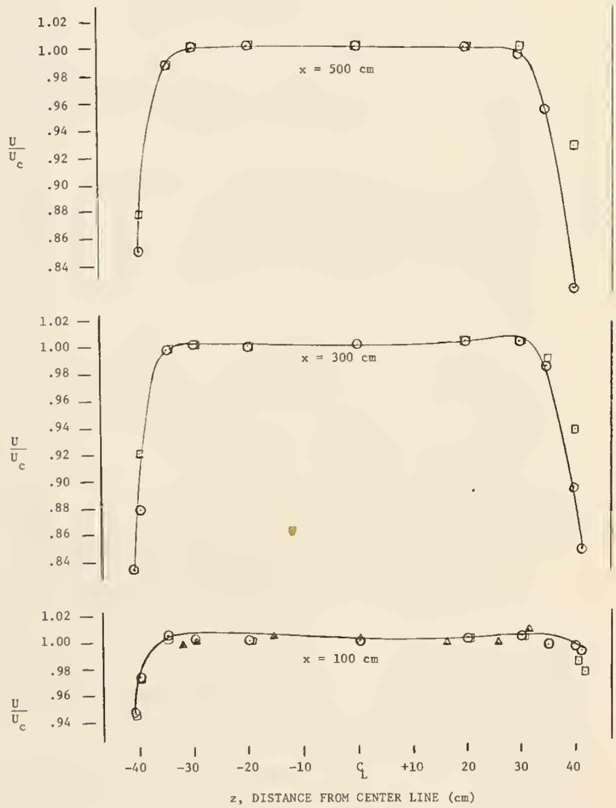

Figure 13. Velocity distributions (vertical through centerline), ⊙ U_c = 322 m/min, Pitot-static tube, △ U_c = 322 m/min, laser velocity standard, ⊡ U_c = 567 m/min, Pitot-static tube.

A comparison, illustrating the very good agreement obtained using both methods at x = 100 cm, and U_c = 322 m/min is also shown in figures 12 and 13. As has been previously demonstrated, it is necessary to use the laser system for an accurate evaluation of the uniformity of the flow at very low velocities. Distributions of velocity in the horizontal and vertical directions about the

centerline obtained with the laser system at x = 100 cm, and U_c = 12.2 m/min are shown in figure 14.

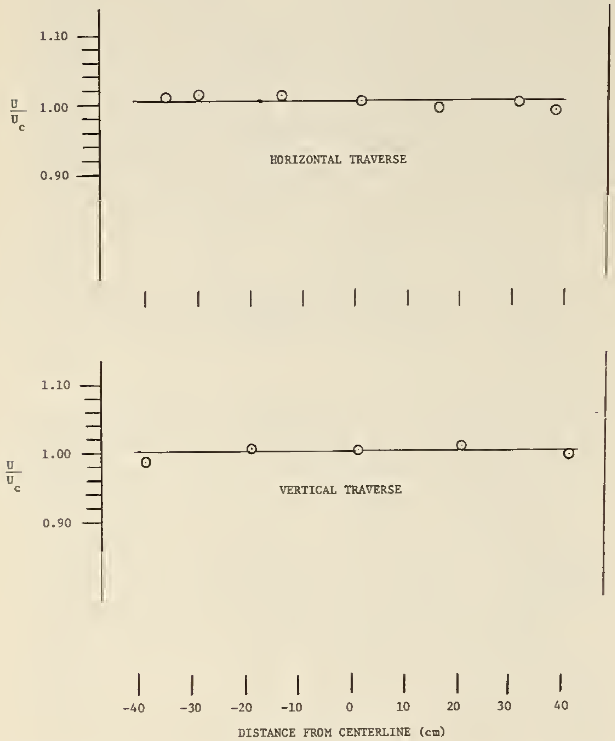

Figure 14. Velocity distributions measured with laser velocity standard at x = 100 cm, U_c = 12.2 m/min.

It is seen that a good degree of uniformity in mean velocity exists at this low velocity. The mean flow characteristics were mapped in great detail at x = 100, 300, and 500 cm, for a centerline velocity of 322 m/min. The results of such measurements are given in Figures 15, 16 and 17, which show an estimate of the contour of the test "window," i.e., the region over which the flow is uniform to within ± one percent. The shape of the contours is as expected, and reflects the presence of secondary flow in the corners and the downstream boundary layer growth. The results illustrate that a satisfactory "window" exists over the speed range of the facility, and the length of the test section.

The remaining factor pertaining to the performance of the flow facility that requires comment is the residual turbulence. Turbulence measurements on the centerline, at x = 300 cm, were made by constant temperature hot-wire anemometry that had a low frequency cutoff of 0.2 Hz. The turbulence intensity, i.e., the ratio of the rms value of the longitudinal component of the velocity fluctuations, u', to U_c, and its variation with U_c, is shown in figure 18. The turbulence level achieved is comparable to levels in good low turbulence flow facilities, and is sufficiently low to avoid any significant statistical bias of the individual realizations of velocity by the laser system.

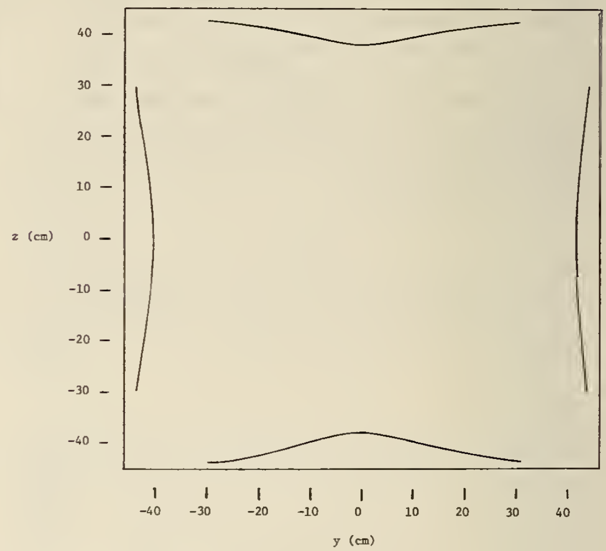

Figure 15. Test "window" at x = 100 cm, U_c = 322 m/min.

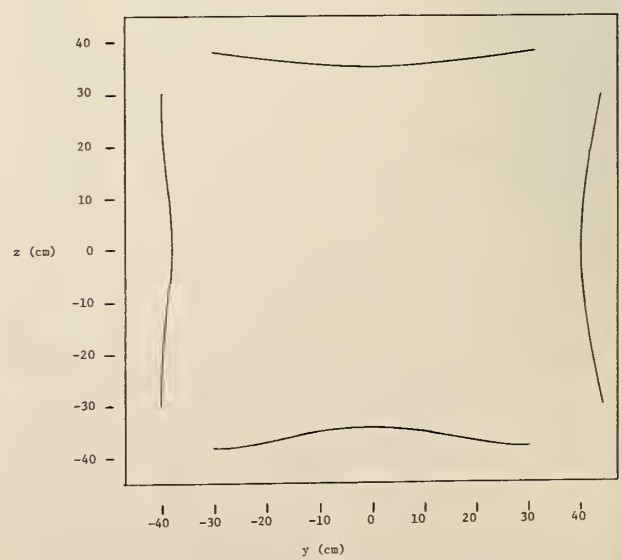

Figure 16. Test "window" at x = 300 cm, U_c = 322 m/min.

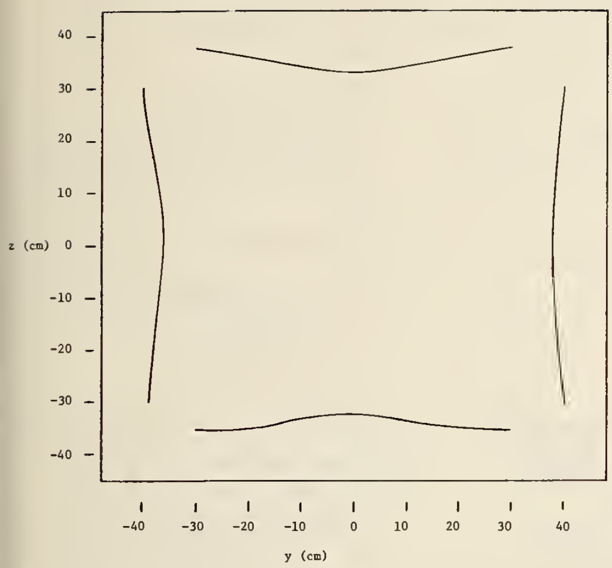

Figure 17. Test "window" at x = 500 cm, U_c = 322 m/min.

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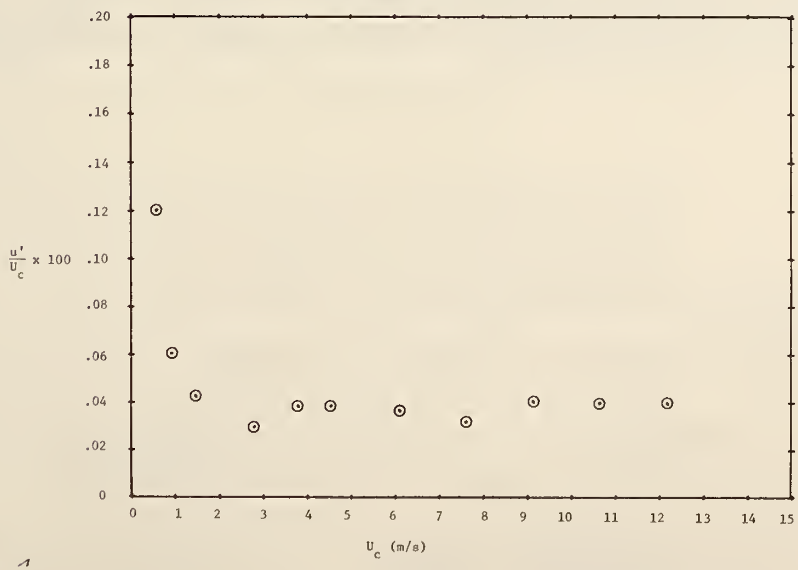

Figure 18. Variation of turbulence intensity with centerline velocity.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A low-velocity airflow facility suitable for the calibration of wind speed measuring instruments and research in aerodynamics is described. The flow facility is of the open-return type with a test section 20 feet (6.1 meters) long, and nominally 3 x 3 feet (0.91 x 0.91 m) in cross section. Special attention was given to obtaining an air stream with a high degree of spatial uniformity and low turbulence with excellent speed control over the range from 3 to 1000 meters (10 to 3300 feet) per minute. Laser-optical methods with appropriate signal processing electronics are employed to establish a primary standard for the measurement of very low velocities. A crossed-beam dual-scattering laser-optical system is used that can operate with either forward or backscattering, and in a frequency shifted Bragg cell mode, or in a non-frequency shifted optical beam-splitter block mode. Detailed performance characteristics of the flow facility and the laser velocity standard are presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Airflow; calibration; facility; laser optics; low velocity; mine ventilation; velocity standard.

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